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HEAVY MINERALS IN SANDS ALONG THE WABASH RIVER

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ABSTRACT

The heavy mineral fractions of 30 samples of sands and gravels collected along the Wabash River were studied to determine the kinds and amounts of minerals—especially titanium minerals—that were present. The samples were taken primarily from terrace deposits composed of glacial outwash, from recent river bar deposits, and from sand dunes. Mineralogic, chemical, and X-ray diffraction analyses were made of the heavy fractions.

The heavy fractions are composed principally of the silicate minerals hornblende and garnet, the iron-titanium and iron oxide minerals magnetite, ilmenite, and hematite, and heavy rock fragments. Most of the heavy minerals in the samples are coarser than 270-mesh and finer than 35-mesh.

Most of the samples have between 1 and 3 percent heavy minerals, including 0.02 to 0.3 percent ilmenite. The amount of TiO_2 contained in titanium mineral grains is estimated to range from 0.01 to 0.17 percent. These values are much lower than those of Florida sand deposits that are being mined for their titanium minerals.

The finer size grades in any sample of Wabash Valley sand or gravel contain the highest amounts of titanium-bearing minerals. The finer size grades of some samples have TiO_2 contents closely approaching the amounts in the Florida sands. However, the mineral separation problems in the Wabash Valley sands appear much more difficult than the problems in the Florida sands. The possibility of marketable by-products in the Wabash Valley sands is uncertain, and the likelihood of by-products as valuable as those of the Florida sands appears very doubtful.

The possibility of commercial use of the heavy minerals in sands along the Wabash River appears questionable at present.

INTRODUCTION

Purpose of Study

Heavy minerals, having a specific gravity greater than 2.85, occur in all sands. Some sands contain large enough concentrations of valuable heavy minerals to serve as commercial sources of these minerals. The kinds of heavy minerals occurring in Illinois river and glacial outwash sands, including the Wabash River sands, have been known fairly well for some time (Lamar and Grim, 1937), but the amounts of the more valuable heavy minerals have never been considered great enough to warrant commercial exploitation. Local interest in the heavy minerals of the Wabash River sands, however, especially the titanium minerals, seemed to justify a detailed, quantitative study. This study seemed especially desirable because ilmenite, the most common titanium mineral, is opaque and difficult to distinguish from other opaque minerals, and, therefore, the amount of ilmenite in the sands was known with less certainty than the amounts of most other minerals.

Previous Investigations

Sand and gravel deposits in the Illinois counties adjoining the Wabash River were mapped by Malott (1930a and b; 1931a, b, c, d, and e). Fidlar (1948) and Thornbury (1950) have discussed the deposits of Pleistocene age occurring in the Lower Wabash Valley. The general mineralogic compositions of two samples of Wabash River sand were determined by Willman (1942) and Hunter (1965). McCammon (1961) described the types of pebbles occurring in the terrace gravels of the Wabash Valley. The heavy minerals in one sample of Wabash River sand were identified by Lamar and Grim (1937). Willman, Glass, and Frye (1963) and Frye, Glass, and Willman (1962) studied the heavy minerals occurring in the glacial tills and loesses of the Illinois portion of the Wabash drainage basin.

TYPES OF DEPOSITS

Heavy minerals are found to some extent in all the earth materials along the Wabash River. However, it is only in water-laid or wind-laid unconsolidated sediments containing substantial amounts of sand-sized grains that heavy minerals are at all likely to occur in amounts and physical form suitable for commercial extraction. Gravel deposits as well as sand deposits are possible heavy mineral sources because many gravel deposits contain much sand-sized material. Sand and gravel deposits are found along the Wabash River in the alluvium deposited by the river in post-glacial times, in glacial outwash, and in sand dunes (fig. 1).

Alluvium

Sand bars and gravel bars, deposited during times of high water level and exposed at times of low water level, are found in many places along the Wabash River. As a general rule, the ratio of sand to gravel in the bars increases downstream, but there is much local variation. Sand and gravel also occurs in the river bed itself and is dredged in several places.

The floodplain of the Wabash River is underlain primarily by clay and silt to depths of at least 10 or 20 feet, as revealed in numerous places where the river has cut into its own floodplain deposits. However, the floodplain does contain fine-grained sand at the surface in some places.

The alluvium in the Wabash Valley probably extends little deeper than the bottom of the present river channel, and it overlies thick glacial outwash sand and gravel in most places.

Glacial Outwash

Sand and gravel outwash from glaciers of Wisconsinan age filled the Wabash Valley to a level higher than the present river, and remnants of this outwash are preserved as terraces along the river. A high-level terrace, called the Shelbyville Terrace by Fidlar (1948), is found 40 to 60 feet above present river level in Clark and Crawford Counties (fig. 1) but is not preserved south of Crawford County. A low-level terrace, termed the Maumee Terrace by Fidlar (1948), occurs 20 to 40 feet above the level of the Wabash River throughout its length in Illinois. The low terrace is probably an erosional surface cut on the same material that forms the high terrace (Fidlar, 1948, p. 71), although the evidence is not conclusive (Thornbury, 1958). The proportion of sand in the glacial outwash increases downstream. Commonly, the outwash is over 100 feet thick (Fidlar, 1948, p. 22; Thornbury, 1950).

The valleys tributary to the Wabash Valley became slackwater lakes when the floods of glacial meltwater were depositing sand and gravel in the Wabash Valley. The lakes became filled mainly with silt deposits, remnants of which are preserved as terraces along the tributary streams. These terraces are at the same level as the high terrace, where it is preserved in the adjacent Wabash Valley, or 35 to 60 feet above the level of the Wabash River, south of the area where the high terrace is preserved. Where the tributary valleys join the Wabash Valley, their terraces contain sand as well as silt.

Sand Dunes

Sand has been blown from the glacial outwash and heaped into dunes that cover parts of the high- and low-level terraces, slackwater lake deposits, and adjacent uplands. Most of this wind action took place in glacial times. Dunes are most common on the slackwater lake deposits adjacent to the Wabash Valley in southern Wabash County and in White County east of Carmi. The dune sand is better sorted and finer grained than most of the alluvial and glacial outwash sand.

METHODS OF INVESTIGATION

Sampling

Samples of sand and gravel were taken from terrace and river bar deposits, from sand dunes, and, to a lesser extent, from floodplain deposits and waste sand from gravel operations (table 1 and fig. 1). The samples from the terrace, dune, and floodplain deposits are channel samples; a channel sample is taken from a

trench that extends from the top to the bottom of the outcrop. The bars and waste sand are not exposed in vertical cuts and therefore were "spot" sampled. In spot sampling, a series of small samples was taken across the surface of the deposit. Only the upper one or two feet of the deposit is represented by spot sampling. The help of Edward C. A. Runge, in acquiring one drill hole sample of sand (sample 25), is gratefully acknowledged.

Preparation of Samples

Samples were sieved for ten minutes on Tyler standard sieves using a Ro-tap shaker, and thereby separated into 4 fractions—coarser than 4-mesh, 4- by 35-mesh, 35- by 270-mesh, and finer than 270-mesh (fig. 2). The 35- by 270-mesh sieve grade contained most of the heavy minerals in the samples; therefore, further work was devoted principally to it.

The 35- to 270-mesh sieve grade was treated with hydrochloric acid to remove surface stains of iron oxides on the grains. It also removed carbonate grains. Microscopic examination revealed a surface roughness on some hematite grains that may have been caused by slight acid etching, but no other effects of the acid treatment on the heavy minerals were noted.

After acid treatment, the material was placed in a separatory funnel with bromoform, a liquid having a specific gravity of about 2.85, and divided into a heavy or "sink" fraction and a light or "float" fraction.

The heavy fraction of the 35- to 270-mesh sieve grade was separated into strongly magnetic, slightly magnetic, and nonmagnetic fractions. The strongly magnetic fraction consisted of those grains attracted to a small alnico permanent magnet held about 0.1 inch above the grains. The slightly magnetic fraction consisted of those grains attracted to the pole piece of a laboratory electromagnet held about 0.1

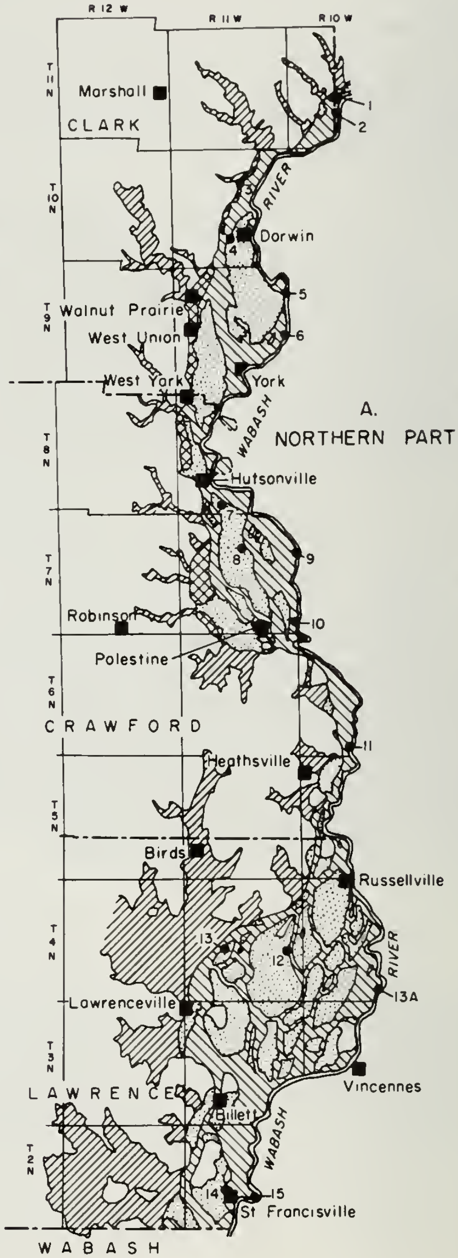
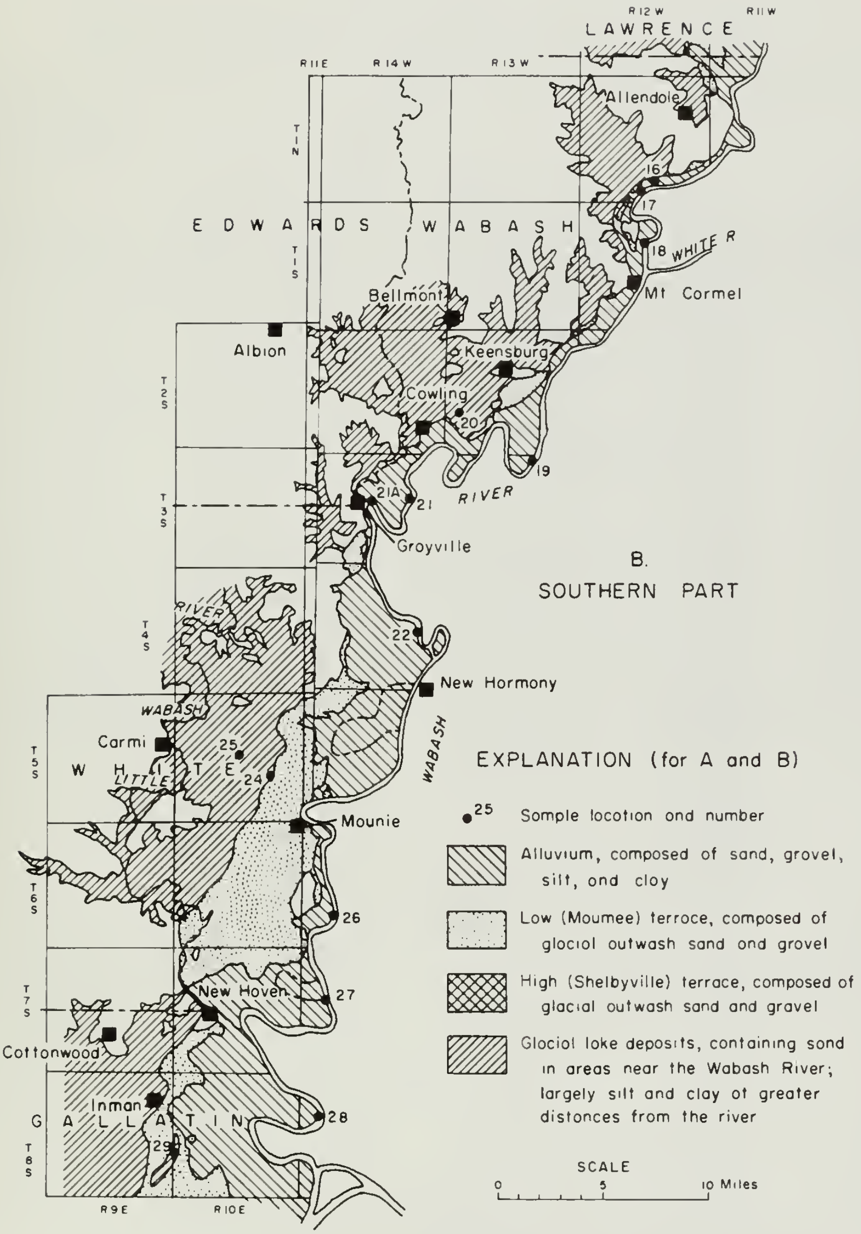


Figure 1 - Sample locations and
Valley. A. Northern



distribution of sand and gravel deposits in the Illinois portion of the Wabash part. B. Southern part. Slightly modified from Fidlar (1948, plate 1).

TABLE 1 - LOCATION, DESCRIPTION, AND SIEVE ANALYSES OF SAMPLES

Sample number	Location							Type of sample	Thickness sampled (ft)	Type of deposit	Sieve analysis: Sieve size in mesh (percent by weight)			
	County	¼	¼	¼	Sec.	T.	R.				+4	4 x 35	35 x 270	-270
1	Vigo (Ind.)	NW	NE	SW	21	11N	10W	Channel	3	High terrace	50.1	26.6	19.6	2.0
2	Vigo (Ind.)	SW	SE	NW	28	11N	10W	Spot	2	River gravel bar	45.1	42.3	12.0	0.5
3	Clark	NE	SW	SE	10	10N	11W	Channel	15	High terrace	17.6	50.3	30.8	1.0
4	Clark	SW	NE	SE	28	10N	11W	Channel	6	Low terrace	43.6	22.2	33.4	1.1
5	Clark	NE	SW	NE	12	9N	11W	Spot	1	River gravel bar	50.8	39.3	9.6	0.3
6	Clark	SW	SE	SW	24	9N	11W	Channel	4	Floodplain	0.0	11.8	76.0	12.2
7	Crawford	SW	SW	NE	33	8N	11W	Channel	5	Low terrace[1]	4.3	16.3	76.0	3.1
8	Crawford	SE	SE	SW	10	7N	11W	Channel	5	Low terrace	45.5	34.9	18.5	1.3
9	Crawford	NW	NW	NW	18	7N	10W	Spot	1	River sand bar	10.4	40.2	48.8	0.3
10	Crawford	SE	SE	NE	36	7N	11W	Spot	1	River sand bar	0.0	12.9	85.2	1.7
11	Crawford	NW	SW	SE	33	6N	10W	Spot	1	River gravel bar	39.1	35.2	24.2	1.3
12	Lawrence	SE	SE	NW	24	4N	11W	Channel	7	Low terrace	31.2	51.5	16.7	0.4
13	Lawrence	NE	SW	NW	21	4N	11W	Channel	4	Low terrace	46.8	21.8	30.8	0.6
13a	Lawrence	NW	SE	SE	34	4N	10W	Spot	1	River sand bar	0.0	24.8	75.0	0.2
14	Lawrence	SE	SE	SE	17	2N	11W	Channel	10	Sand dune	0.0	2.5	90.6	7.0
15	Lawrence	SW	SE	NE	22	2N	11W	Spot	1	River sand bar	0.0	3.8	95.5	0.6
16	Wabash	NE	SE	SW	27	1N	12W	Channel	3	Low terrace (?)	37.2	33.0	28.1	1.4
17	Wabash	SE	NW	NE	33	1N	12W	Spot	1	Waste sand from gravel dredging[2]	0.0	45.5	53.9	0.3
18	Wabash	NE	NE	NE	16	1S	12W	Spot	1	River sand bar	2.7	49.5	47.7	0.2
19	Wabash	SW	NE	NE	10	3S	13W	Spot	1	River sand bar	1.7	65.2	32.8	0.3
20	Wabash	SE	SE	SW	19	2S	13W	Channel	10	Sand dune	0.0	0.2	92.1	7.7
21	Wabash	NE	NW	NE	23	3S	14W	Spot	1	River sand bar	13.6	57.0	29.4	0.1
21a	Wabash	SW	NE	NE	21	3S	14W	Spot	1	River sand bar	0.0	34.4	64.7	0.9
22	White	SW	NW	NW	24	4S	14W	Spot	1	River sand bar	10.1	66.2	23.4	0.3
24	White	NW	NE	NE	27	5S	10E	Channel	7	Sand dune	0.0	5.2	92.2	2.7
25	White	NW	NW	NW	22	5S	10E	Drill hole	1	Low terrace[3]	0.0	5.0	94.3	0.7
26	White	SW	SW	NE	29	6S	11E	Spot	1	River gravel bar	44.2	34.0	21.7	0.1
27	White	NW	NE	SW	17	7S	11E	Spot	2	River sand bar	0.8	36.3	63.2	0.2
28	Gallatin	NE	NE	NE	18	8S	11E	Spot	1	River sand bar	0.9	57.4	41.5	0.2
29	Gallatin	NW	NW	NW	30	8S	10E	Channel	2	Sand dune	0.0	0.1	94.4	5.0

[1] Collected from upper sandy zone in gravel pit.
[2] Collected from head of alluvial fan built of sand issuing from flume at gravel-washing operation.
[3] Uppermost well sorted sand in drill hole, at depth of 7 feet.

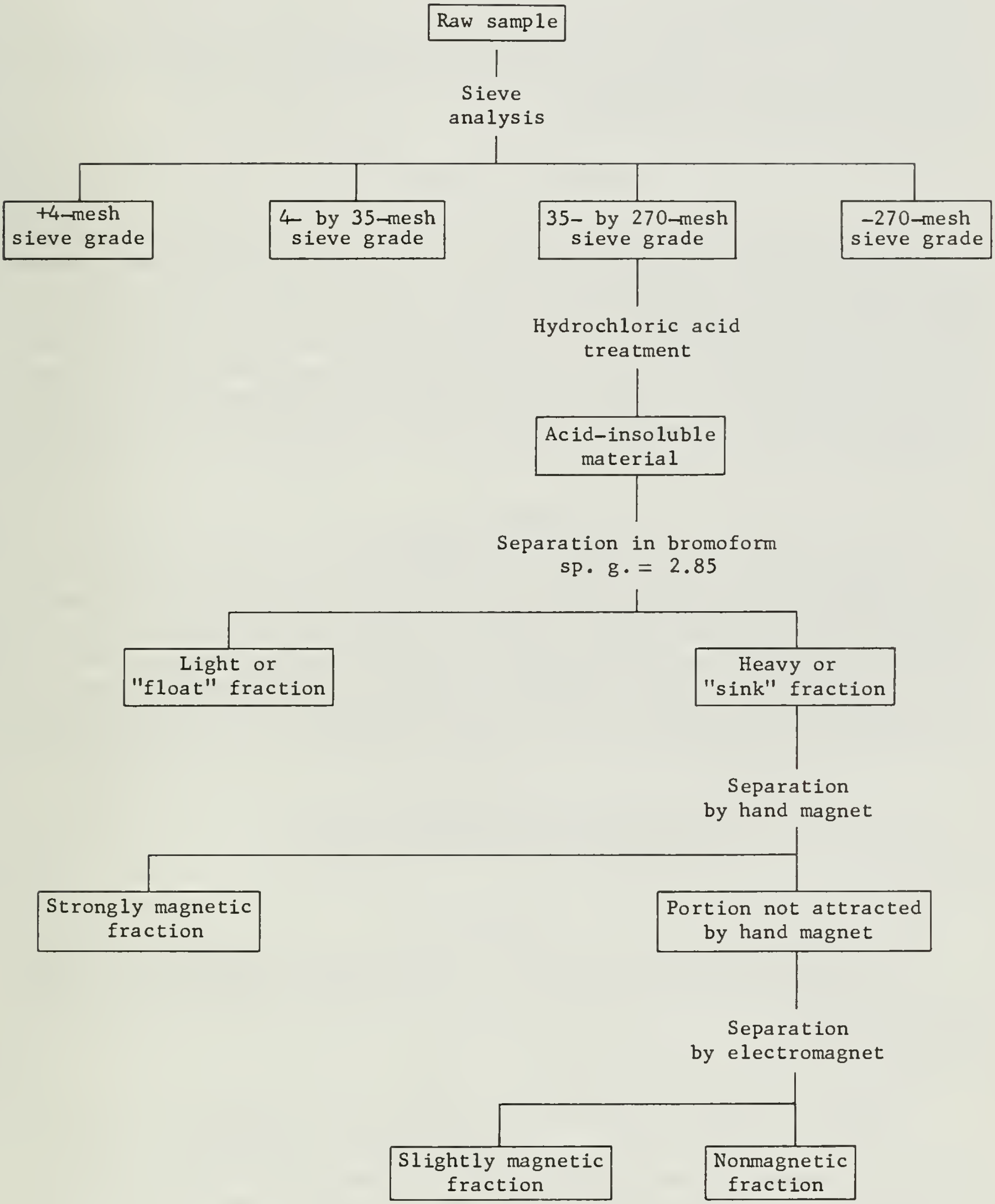


Figure 2 - Flowsheet showing standard treatment for all samples.

inch above the grains. The nonmagnetic fraction consisted of those grains not attracted to the electromagnet.

In order to obtain more detailed information on the size distribution of the heavy minerals, four samples were sieved on a complete $\sqrt{2}$ mm series of Tyler sieves, and each sieve grade was treated in the same manner as the 35- to 270-mesh sieve grades of other samples.

Mineralogic Analyses

The strongly and slightly magnetic fractions were examined with a binocular microscope. The nonmagnetic fraction was examined with a petrographic microscope, with the opaque grains illuminated by a subsidiary light source obliquely above the grains. Two hundred grains, randomly encountered in each magnetic fraction of the heavy fraction of a sample, were identified. The diameters of the grains, as measured by a micrometer ocular, were also recorded. The percentages of the minerals by numbers of grains were converted to weight percentages by applying correction factors related to specific gravity and average grain diameter of the mineral.

Chemical Analyses

Partial chemical analyses of selected samples were made by the X-ray fluorescence method. Titanium and iron contents of all magnetic fractions were determined. The zirconium content of the nonmagnetic fraction also was determined. Samples selected for analysis included representative types and those having unusually high contents of titanium minerals. In order to interpret the chemical analyses more thoroughly, the minerals present in the chemically analyzed samples were identified by X-ray diffraction as well as by microscopic means.

MINERALOGIC COMPOSITION OF THE HEAVY FRACTIONS OF THE SANDS

Constituents

The heavy constituents of the sands include various minerals and rock fragments. Rock fragments were identified as a group rather than in terms of their individual minerals.

Iron-Titanium and Iron Oxide Minerals

Ilmenite ($FeTiO_3$), magnetite (Fe_3O_4), and hematite (Fe_2O_3) are common constituents of the Wabash Valley sands. All three are usually black, opaque or very nearly opaque, and have metallic lusters. Some of the hematite, however, is dark red, and a few grains of ilmenite are partially coated by leucoxene, a white to light brown alteration product. Ilmenite is the principal commercial source of titanium metal and compounds, and the other two minerals form iron ores where they occur in large enough concentrations.

Strongly magnetic types.—Magnetite was the principal strongly magnetic mineral in the sands. X-ray diffraction powder patterns of the three magnetic frac-

tions revealed magnetite only in the strongly magnetic fraction, which indicates that essentially all the magnetite was separated by the procedure used. X-ray diffraction powder patterns of the strongly magnetic material reveal, besides magnetite, small amounts of ilmenite and/or hematite in most samples. This ilmenite and hematite may be present as (1) inclusions within magnetite grains, (2) constituents of strongly magnetic rock fragments, and (3) separate grains. Calculations from chemical analyses indicate that the strongly magnetic black opaque mineral fraction of the Wabash Valley sands contains about 10 percent TiO_2. Some of this may be present in solid solution in the magnetite, and the rest is probably mainly in the form of ilmenite occurring as in 1, 2, and 3 above.

Published data indicate that magnetites from granites and gneisses have titanium contents generally between 1 and 5 percent and that magnetites from basic igneous rocks contain from about 7 to more than 25 percent TiO_2 (Buddington, Fahey, and Vlisidis, 1955; Buddington and Lindsley, 1964). The reported TiO_2 occurs within the magnetite in solid solution and/or as inclusions of titanium minerals that were originally present in solid solution. The source rocks of the magnetite found in the Wabash Valley sands probably include basic igneous rocks as well as granites and gneisses. It seems probable, therefore, that little of the 10 percent TiO_2 found in the strongly magnetic black opaque mineral fraction occurs as separate grains of ilmenite.

Slightly magnetic and nonmagnetic types.—Much of the ilmenite and hematite in the sand is more magnetic than the other heavy minerals, except magnetite. From 30 to 90 percent of the total ilmenite plus hematite in the Wabash Valley sands was attracted to the pole piece of an electromagnet whose field strength was adjusted to give optimum separation results. When stronger magnetic fields were used, large amounts of garnet, other minerals, and rock fragments were attracted to the pole piece along with the remaining ilmenite and hematite. In sands containing relatively small proportions of heavy rock fragments, 70 to 90 percent of the ilmenite plus hematite can be recovered magnetically, and the separate contains less than 5 percent constituents other than ilmenite and hematite.

The relative amounts of ilmenite and hematite in the slightly magnetic and nonmagnetic fractions could not be determined accurately by microscopic observation of loose grains because both minerals were opaque and black or nearly black. However, examination of broken grains, which transmitted light on thin edges, and identification by the criteria proposed by Wallace (1953) revealed that both ilmenite and hematite are common. X-ray diffraction powder patterns show that ilmenite and hematite are present in approximately equal amounts in the slightly magnetic fraction. The amounts in the nonmagnetic fraction are so small that their ratio cannot be accurately judged from the X-ray patterns. Calculations from chemical analyses give the most exact information; they indicate that the ratio of ilmenite to hematite in the slightly magnetic fraction ranges from 0.7 to 1.5 and averages about 1.0. As ilmenite is more magnetic than hematite (Slichter, 1942), the ratio of ilmenite to hematite remaining in the least magnetic fraction is certainly no higher than it is in the slightly magnetic fraction.

Microscopic investigation of hematite grains, broken so that they transmit light on thin edges and distinguished from ilmenite by the criteria suggested by Wallace (1953), reveals that the grains are made up of a few hematite crystals or perhaps, in many cases, are monocrystalline. Few, if any, of the hematite grains are earthy alteration products of other minerals. Detrital hematite has not been previously reported from Illinois sands, but its unexpected abundance in the Wabash Valley sands does not seem unusual, as several recent studies suggest that

TABLE 2 - MINERALOGIC COMPOSITION OF 35- BY 270-MESH SIEVE GRADE AND HEAVY FRACTION

	Composition of sieve grade (weight percent)			Composition of heavy fraction (weight percent)																
				Nonmagnetic												Slightly magnetic			Strongly magnetic	
Sample number	Soluble in HCL	Insoluble light fraction	Insoluble heavy fraction	Rock fragments	Hornblende	Actinolite-tremolite	Augite-diopside	Hypersthene-enstatite	Epidote	Garnet	Others	Zircon	Titanite	Rutile	Ilmenite-hematite	Ilmenite-hematite	Silicate minerals	Rock fragments	Magnetite	Rock fragments
1	23.8	68.1	8.1	36	21	.4	2	.4	.2	7	.4	.5			3.4	10.8	.5	3.9	10.4	3.0
2	11.2	83.4	5.4	12	22	2	4	3	4	28	1	.6	1.1	.5	2.6	13.4	.8	.9	3.6	.7
3	15.8	80.4	3.8	33	17	1	5	1	5	19		.2	1.3		2.3	5.1	.4	3.0	5.1	1.7
4	20.3	73.1	6.6	31	10	1	4	.5	4	19	.8	.6	.5	.3	6.1	8.5	.8	1.1	10.7	1.4
5	7.0	82.5	10.5	7	6	1	1	.5	2	39	.3	.5	.2		11.2	17.3		.6	13.3	.2
6	19.2	78.4	2.4	13	34	6	5	3	9	9	2	2.0	2.1		3.6	7.3	.7	1.8	1.3	.3
7	19.5	76.5	4.0	16	20	3	5	.9	3	27	.6	1.2	.9		6.5	5.7	.6	2.3	5.3	1.7
8	23.3	71.8	4.9	30	13	2	4	1	2	25	.3	.3	.5	.3	4.8	8.6	1.1	2.5	3.1	1.3
9	6.0	91.8	2.2	27	29	3	6	3	7	12	1	.6	.4		1.3	6.4	.3	1.8	1.0	.4
10	7.5	89.6	2.9	31	24	3	5	3	3	11	.4	1.1	1.1	.4	5.7	3.9	.4	1.9	4.0	1.5
11	7.7	87.8	4.5	32	14	.5	4	1	3	19	.3	.2	.5		2.3	15.1	.3	2.8	4.3	.8
12	22.0	73.1	4.9	36	14	1	6	2	6	13	.7	.6	1.0		1.7	7.4	.8	2.4	5.3	2.4
13	8.2	86.9	4.9	27	14	2	3	2	2	23	.5	.2	.5	.6	1.9	12.5	1.1	2.4	5.7	1.7
13a	7.0	90.9	2.1	40	23	3	4	4	2	12			.8	.3	1.2	2.8	.3	2.3	1.9	2.3
14	13.5	84.1	2.4	34	23	2	7	3	5	8	.7	.3	1.0	.7	4.5	3.6	.3	2.5	3.2	1.5
15	5.1	92.6	2.3	23	29	5	6	3	7	11	1	.5	.9	.3	2.7	8.3	.5	1.4	.7	.2
16	8.5	88.5	3.0	23	25	2	3	3	2	17		.7	.9		3.7	11.7	.8	2.5	4.7	.6
17	10.6	82.6	6.8	24	19	2	4	3	3	11	2	.7	1.5		8.8	13.7	.4	.9	5.7	.4
18	6.7	91.3	2.0	24	31	4	6	5	7	9	.5		1.5		3.4	4.6	.2	.9	1.8	.7
19	10.7	86.3	3.0	39	25	2	6	1	3	12	.4	.2	.8		1.6	3.4	.6	2.5	1.2	1.0
20	19.3	77.4	3.3	14	39	4	5	3	6	10	2	.4	3.5		4.4	4.2	.4	.7	2.9	.4
21	10.4	85.1	4.5	40	9	1	1	1	1	20	.8	1.8	.6	.2	2.5	13.5	.1	1.5	5.1	1.0
21a	7.4	90.3	2.3	25	30	3	8	3	5	8	1	.9			4.4	6.1	.9	1.8	2.0	.7
22	5.4	89.6	5.0	33	19	1	3	2	4	17		.5	.7	.6	1.7	10.9	.7	2.5	3.0	.7
23	4.5	92.0	3.5	14	31	2	3	2	5	19	.4	2.6	.4	.5	7.3	9.0	.2	1.0	2.3	.3
24	2.5	96.2	1.3	25	36	3	7	3	6	6	.4	.4	1.2	.5	1.7	6.4	.4	1.1	1.4	.2
25	10.2	81.2	8.6	20	10	.4	2	.9	.9	28		.5	.4	.2	3.0	22.6	.5	2.0	7.7	1.1
26	8.7	89.4	1.9	28	33	3	8	6	7	7					1.2	2.1	.4	2.1	.9	1.7
27	8.6	87.1	4.3	37	15	1	5	1	5	14	1	.8	1.9	.3	2.3	10.3	.2	1.8	2.7	.8
28	18.8	78.7	2.5	12	37	3	8	4	7	11	2	.5	1.8	.5	5.5	3.2	.7	.8	2.9	.5

detrital grains composed of hematite are more common than has been previously supposed (Irving, 1957, p. 101-103; Runcorn, 1959, p. 1005; Thorsen, 1964; Van Houten, 1961).

Other Titanium Minerals

Titanite, or sphene ($CaTiSiO_5$), is present in small amounts, generally forming less than 2 percent of the heavy fraction. Rutile (TiO_2) occurs in very small amounts, averaging about one-third as much as titanite. Both minerals were found only in the nonmagnetic fraction.

Zircon

Zircon is found in small amounts, generally less than 2 percent of the heavy fraction. It was found only in the nonmagnetic fraction. Zircon is the source of zirconium oxide, used as a refractory.

Silicate Minerals

Various complex silicates of Al, Mg, Fe, Ca, and other elements are common minerals in the Wabash Valley sands. Some of these, especially garnet, are used as industrial minerals where they occur in large enough concentrations.

The most common silicate mineral is hornblende, which appears black to the unaided eye but is green to olive brown in transmitted light. Garnet, largely of the almandine variety, is also common, occurring as red to colorless grains. Other fairly common silicate minerals are the amphiboles tremolite and actinolite, the clinopyroxenes angite and diopside, the orthopyroxenes hypersthene and enstatite, and epidote. Silicate minerals occurring in small amounts and grouped under "others" in table 2 are biotite, muscovite, tourmaline, zoisite, staurolite, kyanite, and sillimanite.

Pyrite

Spherical concretionary grains of pyrite (FeS_2), and loosely bound aggregates of such grains, occur in some samples. The grains are of fine sand size. They are uncommon and are grouped under "others" in table 2.

Rock Fragments

A rock fragment is an aggregate of several minerals in a single detrital grain. Included in this category may be some originally single-mineral grains altered to finely crystalline aggregates. The heavy rock fragments are mainly fragments of intermediate to basic igneous and metamorphic rocks. Many of the heavy rock fragments consist largely of light minerals but contain enough heavy minerals to make their specific gravity greater than 2.85. Some heavy rock fragments contain enough magnetic minerals to be slightly or strongly magnetic. These accompany the iron-titanium and iron oxide minerals during magnetic separations.

Some of the rock fragments are opaque or nearly so and white to light brown in reflected light. Most of these grains may be distinguished from leucoxene by their more coarsely granular appearance in reflected light or convergent transmitted light. The fact that such grains are most abundant in size grades coarser than those containing most of the ilmenite also suggests that very few of these grains are leucoxene. The rarity of partial coatings of leucoxene on ilmenite grains is further evidence against the presence of many leucoxene grains.

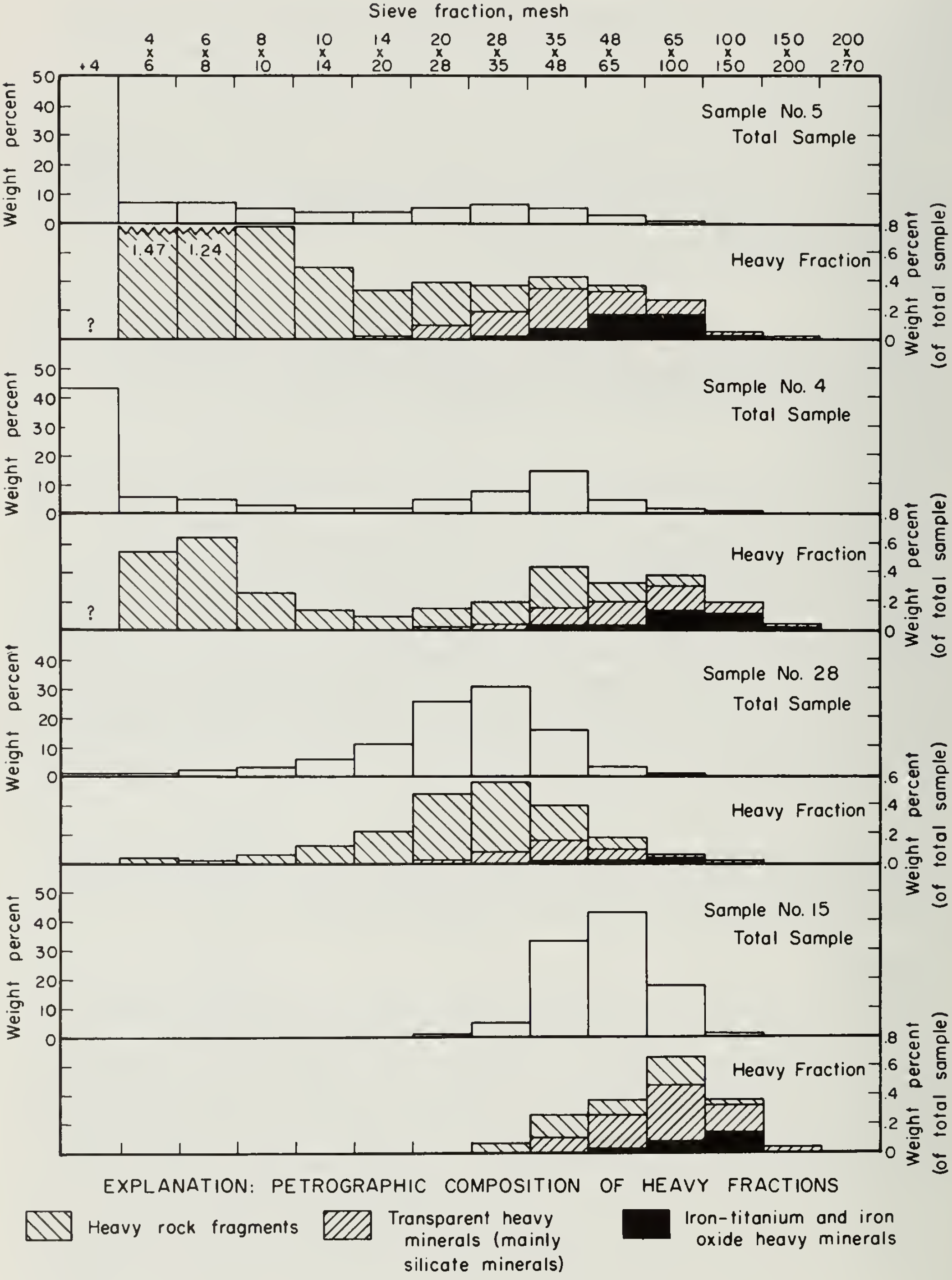


Figure 3 - Size distributions of four Wabash Valley samples and of their heavy fractions, and petrographic compositions of the heavy fractions.

Size Distribution of Heavy Minerals

In the samples studied, the heavy minerals occur predominantly in the 35- to 270-mesh sieve grade. Heavy rock fragments are commonly coarser than 35-mesh, but these are of no known economic interest. Some of the samples, especially the coarser ones, contain heavy minerals coarser than 35-mesh. In sample 5, the coarsest sample collected, 24 percent of the heavy minerals are coarser than 35-mesh; however, only 6 percent of the iron-titanium and iron oxide minerals are coarser than 35-mesh, and probably no other sample has as much. Some heavy mineral grains are finer than 270-mesh, but most of the samples contain negligible amounts of material of this grain size. Only samples 6, 14, 20, and 29 contain more than 5 percent material finer than 270-mesh. In sample 20, 16 percent of the heavy fraction is finer than 270-mesh, and 28 percent of the analyzed TiO_2 is in the material finer than 270-mesh. It is estimated that over nine-tenths of the titanium-bearing minerals are contained in the 35- to 270-mesh material, except for those samples containing more than 5 percent material finer than 270-mesh.

In a given sample, the heavy minerals are primarily finer grained than the average grain size or modal size grade of the whole sample (fig. 3). This is true both in coarse- and fine-grained samples. In the detailed study of four samples, shown in figure 3, more than 75 percent of the heavy minerals were contained in sieve grades finer than that which contained the greatest percentage of total sand-sized grains, that is, the mode or, if the sample was bimodal, the mode in the sand size range.

In general, this same relation is true of the individual heavy minerals. The heavy minerals having the greater specific gravities, such as the iron-titanium and iron oxide minerals, tend to be finer grained than those having lesser specific gravities (fig. 3). In the detailed study of four samples, more than 90 percent of the iron-titanium and iron oxide minerals were contained in sieve grades finer than that which contains the greatest percentage of total sand-sized grains.

Amounts of Heavy Minerals

Streaks of black sand consisting almost wholly of heavy minerals can be found along the surface of the river bank in places. Any one of these streaks, however, is only a fraction of an inch thick, a few square feet in area, and forms an insignificant volume of material. Mining these black sand streaks would be impossible without including the ordinary sands, silts, or clays on which they rest. For this reason, the samples analyzed in this report represent, as nearly as possible, the whole deposit as it would be mined. In the analyzed samples, the amount of heavy constituents in the 35- by 270-mesh sieve grade varies from 1.3 to 10.5 percent (table 2).

This large variation is related mainly to the grain size of the sample. Those samples containing less than 25 percent material coarser than 4-mesh contain between 1.3 and 5 percent heavy constituents in the 35- by 270-mesh sieve grade, and those samples containing over 25 percent material coarser than 4-mesh contain between 3 and 10.5 percent heavy constituents in the 35- by 270-mesh sieve grade. Sample 17 is an exception, as it contains a larger heavy fraction than would be expected from its grain size. The reason for this is that it represents the waste sand from a gravel dredging operation; its heavy mineral content is similar to that of the sand fraction of a gravel sample.

Because those samples containing large amounts of +4-mesh material contain little material in the 35- to 270-mesh size range, the percentage of heavy minerals in the whole sample shows less variation from sample to sample than does the percentage of heavy minerals in the 35- to 270-mesh sieve grade. Most of the whole samples have between 1 and 3 percent heavy minerals.

The percentages of the various heavy minerals and rock fragments in the heavy fraction show variations from sample to sample as large as the variation in the percentage of heavy fraction. These variations also are related mainly to the grain size of the sample. The heavy minerals having the highest specific gravities, such as the iron-titanium and iron oxide minerals, tend to be most abundant in the samples containing the largest amounts of +4-mesh material. The heavy constituents having the lowest specific gravities, such as hornblende and the heavy rock fragments, tend to be most abundant in the finest grained samples.

The amount of ilmenite plus hematite in the heavy fraction of the 35- to 270-mesh sieve grade varies from 3 to 29 percent (table 2). As discussed previously, about half of the microscopically identified ilmenite plus hematite is ilmenite. The highest amounts tend to be found in the samples containing the most +4-mesh material. In the whole 35- by 270-mesh sieve grade, ilmenite plus hematite varies from 0.06 to 3.0 percent, the higher figures again being reached in the coarser grained samples. Because the coarser grained samples contain little material in the 35- to 270-mesh size range, the ilmenite plus hematite in the whole sample shows less variation from sample to sample—from 0.04 to 0.6 percent. The greatest amount was in a dune sand sample, number 24.

Titanite, rutile, and zircon are present in only small amounts in the samples (table 2).

CHEMICAL COMPOSITION OF THE SANDS

TiO_2 Contents Estimated from Mineralogic Analyses

The amounts of TiO_2 in the samples were estimated from the mineralogic compositions of the samples (table 3). In making the calculations, it was assumed that (1) half of the microscopically identified ilmenite plus hematite was ilmenite, and that the ilmenite and hematite were chemically pure $FeTiO_3$ and Fe_2O_3; (2) the combined titanite plus rutile consisted of 3 parts titanite to 1 part rutile; (3) TiO_2 formed 10 percent of the magnetite; (4) a negligible amount of TiO_2 was present in all other minerals and in the rock fragments; and (5) the amount of TiO_2 contributed by the material coarser than 35-mesh and finer than 270-mesh was negligible, except in those samples containing over 5 percent material finer than 270-mesh. In those samples (6, 14, 20, and 29), special estimates were made of the TiO_2 in the material finer than 270-mesh.

The amount of TiO_2 that would be determined by chemical analysis of a whole sample would be greater than that estimated on the basis of the above assumptions, mainly because rock fragments, which are common in all the samples, contain some TiO_2. However, the TiO_2 contained in rock fragments is of no interest from the standpoint of commercially profitable extraction of TiO_2 from the sands. It is uncertain whether the TiO_2 contained in titanite or magnetite is economically of interest. The amount of TiO_2 contributed by ilmenite, which is the most interesting titanium mineral from an economic standpoint, ranges from 62 to 93 percent of the total estimated TiO_2 content and averages about 80 percent (table 3).

TABLE 3 - WEIGHT PERCENT OF TiO_2 ESTIMATED FROM MINERALOGIC ANALYSES

Sample number	Estimated TiO_2 in whole sample	Estimated TiO_2 in 35- to 270-mesh sieve fraction	Estimated TiO_2 in heavy fraction of 35- to 270-mesh sieve fraction	Total TiO_2 in ilmenite	Total TiO_2 in titanite and rutile	Total TiO_2 in magnetite
1	0.07	0.38	4.7	79	0	21
2	0.03	0.28	5.2	80	12	8
3	0.03	0.11	2.9	66	17	17
4	0.11	0.34	5.2	73	6	21
5	0.10	1.01	8.8	84	1	15
6	0.13[1]	0.09	3.7	75	22	3
7	0.12	0.16	4.1	78	10	12
8	0.04	0.20	4.0	84	8	8
9	0.02	0.05	2.3	87	9	4
10	0.09	0.10	3.5	72	17	11
11	0.06	0.23	5.1	88	4	8
12	0.03	0.16	3.3	73	12	15
13	0.07	0.23	4.7	78	9	13
13a	0.02	0.03	1.6	62	25	13
14	0.10[2]	0.07	3.1	67	23	10
15	0.08	0.08	3.5	83	14	3
16	0.04	0.15	4.9	82	8	10
17	0.26	0.48	7.1	84	8	8
18	0.03	0.06	2.9	72	21	7
19	0.02	0.05	1.7	76	18	6
20	0.15[3]	0.12	3.5	63	28	9
21	0.07	0.23	5.0	84	6	10
21a	0.05	0.07	2.9	93	0	7
22	0.05	0.20	4.1	81	12	7
23	0.16	0.17	4.8	88	8	4
24	0.04	0.04	3.0	74	23	3
25	0.14	0.66	7.7	87	3	10
26	0.01	0.02	1.0	90	0	10
27	0.08	0.19	4.5	73	20	7
28	0.11[4]	0.09	3.5	66	25	9

[1] Includes an estimated 0.06 percent contributed by material finer than 270-mesh.
[2] Includes an estimated 0.03 percent contributed by material finer than 270-mesh.
[3] Includes an estimated 0.04 percent contributed by material finer than 270-mesh.
[4] Includes an estimated 0.02 percent contributed by material finer than 270-mesh.

The estimated TiO_2 content of the heavy fraction of the 35- by 270-mesh sieve grade ranges from 1.0 to 8.8 percent. In the entire 35- by 270-mesh sieve grade, the estimated TiO_2 content ranges from 0.02 to 1.01 percent. The TiO_2 content of the whole sample is estimated to range from 0.01 to 0.17 percent.

TiO_2 Contents Determined by Chemical Analysis

The results of chemical analyses of selected samples are shown in tables 4 and 5. The TiO_2 content of the heavy fraction of the 35- by 270-mesh sieve grade ranges from 3.1 to 8.4 percent (table 5). The TiO_2 contents determined by chemical analysis agree fairly well with those estimated from petrographic analyses (table 3); the greatest difference is shown by sample 26.

The heavy fraction of the 4- by 35-mesh sieve grade of one sample was analyzed for TiO_2 (table 5). Sample 5 was chosen because it is the most coarse grained of the samples and probably contains the greatest proportion of titanium minerals coarser than 35-mesh. Even in this sample, however, mineralogic analysis indicates that only about 6 percent of the titanium minerals are coarser than 35-mesh and that less than 10 percent of the TiO_2 content shown by chemical analysis of the 4- by 35-mesh heavy fraction can be accounted for by discrete grains

TABLE 4 - WEIGHT PERCENT OF TiO_2, Fe_2O_3, AND ZrO_2 IN THE THREE MAGNETIC FRACTIONS OF SELECTED 35- BY 270-MESH HEAVY FRACTIONS[1] AND CALCULATED MINERALOGIC COMPOSITIONS

Sample number	Magnetic fraction	TiO_2	Calculated ilmenite[2]	Fe_2O_3[3]	Calculated magnetite or hematite[4]	ZrO_2	Calculated zircon	Other constituents	Calculated other constituents[5]
4	non-	4.0	7.8	27.4		0.67	1.0	67.9	
4	slightly	19.2	37.0	67.0	45.9			13.8	17.1
4	strongly	7.3	14.1	84.2	74.9			8.5	11.0
5	non-	5.1	10.0	32.3		1.01	1.55	61.6	
5	slightly	21.0	40.7	75.6	55.1			3.4	4.2
5	strongly	8.1	15.8	88.5	79.8			3.4	4.4
7	non-	2.9	5.6	21.0		0.37	0.56	75.7	
7	slightly	17.2	32.7	51.7	29.1			31.1	38.2
7	strongly	8.5	16.5	81.9	71.1			9.6	12.4
12	non-	2.2	4.3	21.0		0.37	0.56	76.4	
12	slightly	17.2	32.8	58.2	36.9			24.6	30.3
12	strongly	8.9	17.2	78.8	66.9			12.3	15.9
15	non-	2.04	3.9	12.7		0.55	0.83	84.8	
15	slightly	15.6	29.4	42.5	19.2			41.9	51.4
15	strongly	5.5	9.9	53.5	37.8			41.0	52.3
17	non-	4.3	8.4	26.4		0.85	1.3	68.4	
17	slightly	23.7	46.1	73.1	49.9			3.2	4.0
17	strongly	10.8	21.3	89.0	78.4			0.2	0.3
20	non-	2.32	4.5	12.4		0.55	0.83	84.9	
20	slightly	14.4	27.0	43.4	21.1			42.2	51.9
20	strongly	5.7	10.4	59.5	45.1			34.8	44.5
26	non-	1.58	3.1	15.9		0.81	1.2	81.9	
26	slightly	15.0	28.4	48.1	26.3			36.9	45.3
26	strongly	6.4	11.8	59.8	45.1			33.8	43.1
28	non-	1.39	2.7	11.6		0.23	0.35	86.8	
28	slightly	14.8	27.9	43.7	21.3			41.5	50.8
28	strongly	7.4	13.5	49.2	31.1			43.4	55.4

1 Determined by X-ray fluorescence analysis by Miss Juanita Witters.

2 This figure is inaccurate for the nonmagnetic fraction because in that fraction an appreciable part of the TiO_2 occurs in titanite and rutile.

3 All iron is reported as Fe_2O_3.

4 Fe_2O_3 is calculated as hematite in the slightly magnetic fraction and as magnetite in the strongly magnetic fraction.

5 The other constituents in the slightly and strongly magnetic fractions are largely rock fragments. It was assumed, on the basis of the analysis of the 4- to 35-mesh fraction of sample 5 (table 5), that the rock fragments contain 16.0 percent Fe_2O_3 and 1.40 percent TiO_2.

of titanium minerals. The other 90 percent or more of the 1.40 percent TiO_2 shown by the analysis must be present within rock fragments. This amount of TiO_2 is within the range of TiO_2 contents of intermediate to basic igneous and metamorphic rocks, such as make up most of the 4- by 35-mesh heavy fraction.

The heavy fraction of the coarse silt size grade (270-mesh to 0.031 mm) of one sample was analyzed for TiO_2 (table 5). Sample 20 was chosen because it has a relatively high content of material finer than 270-mesh. The TiO_2 content of this fraction, 7.28 percent, is undoubtedly present mainly in the form of discrete titanium minerals, largely ilmenite. Assuming that the light fraction of the 270-mesh to 0.031 mm size grade contains no TiO_2, the TiO_2 content of the whole 270-mesh to 0.031 size grade would be 0.48 percent. A study of the loesses of Illinois, the most abundant silt-sized sediments of the state, has shown from 0.48 to 0.98 percent TiO_2 (Frye, Glass, and Willman, 1962, p. 49). The coarse silt of sample 20, therefore, has a TiO_2 content within the range of common silt-sized sediments of the state.

ZrO_2 Contents

The mineralogic analyses indicate that only small amounts of zircon, the only zirconium mineral identified, are present. This is confirmed by the X-ray fluorescence analyses of ZrO_2 content (tables 4 and 5) of the heavy fractions. The ZrO_2 content of whole samples would be much less than the ZrO_2 contents of the analyzed heavy fractions.

POSSIBLE COMMERCIAL USE OF THE HEAVY MINERALS

No definite conclusions can be made concerning the possibility of commercial use of the heavy minerals without experiments simulating commercial methods of mineral extraction. However, some of the difficulties involved in extracting titanium minerals from the Wabash Valley sands can be seen by comparing them with Florida sands from which titanium minerals are being extracted at the present time. The Florida sands referred to are those of Trail Ridge described by Spencer (1948) and Carpenter et al. (1953). Sands along the Atlantic coast of Florida, also being mined, are similar to those of Trail Ridge (Martens, 1935; Miller, 1945; Giese, Shirley, and Vallely, 1964). The Florida sand deposits have low concentrations of titanium minerals compared to those of India and other parts of the world (Gillson, 1959, p. 421).

The Trail Ridge, Florida, sands contain an average heavy mineral content of 4 percent. Nearly half of the heavy mineral content, or 1.8 percent, is titanium minerals, primarily ilmenite grading into leucoxene. The TiO_2 content of the sand is about 1.1 percent. Humphreys spiral classifiers are used to separate the heavy minerals from the sand, and the titanium minerals are separated from the other heavy minerals by a combination of electromagnetic and electrostatic separators. Zircon and staurolite concentrates are produced as by-products.

Of the Wabash Valley samples, only two dune sands (samples 20 and 24) have 3 percent or more heavy minerals. These same two samples have the highest content of titanium minerals, about 0.3 percent, largely ilmenite. They have less than 0.2 percent TiO_2 present in the form of discrete grains of titanium minerals. The amount of TiO_2 in the best Wabash Valley samples tested is thus less than one-

TABLE 5 - WEIGHT PERCENT OF TiO_2, Fe_2O_3, AND ZrO_2 IN SELECTED HEAVY FRACTIONS[1]

Sample number	Size grade (mesh)[2]	Heavy fraction in size grade	Total TiO_2 in nonmagnetic fraction	Total TiO_2 in slightly magnetic fraction	Total TiO_2 in strongly magnetic fraction	TiO_2 in heavy fraction[3]	Fe_2O_3 in heavy fraction[4]	ZrO_2 in heavy fraction[5]
4	35 x 270	6.6	52	33	15	6.0	38.4	0.52
5	4 x 35	13.2				1.40	16.0	0.05–
5	35 x 270	10.5	42	45	13	8.4	47.7	0.69
7	35 x 270	4.0	54	33	13	4.5	27.8	0.31
12	35 x 270	4.9	42	42	16	4.3	29.5	0.30
15	35 x 270	2.3	52	47	1	3.4	16.1	0.49
17	35 x 270	6.8	44	47	9	7.7	37.5	0.67
20	35 x 270	3.3	68	26	6	3.1	15.6	0.50
20	270 x 0.031 mm	6.6				7.28	33.9	1.70
26	35 x 270	8.6	19	70	11	5.4	27.9	0.54
28	35 x 270	4.3	36	55	9	3.3	17.3	0.19

1 Determined by X-ray fluorescence analysis, by Miss Juanita Witters.
2 Except for the 270-mesh to 0.031 mm size grade of sample 20, the smaller size limit of which was determined by decantation.
3 In all 35- by 270-mesh sieve grades, this figure is calculated from analyses of the three magnetic fractions shown in table 4.
4 In all 35- by 270-mesh sieve grades, this figure is calculated from analyses of the three magnetic fractions shown in table 4. All iron is reported as Fe_2O_3.
5 In all 35- by 270-mesh sieve grades, this figure is calculated from analysis of the nonmagnetic fraction shown in table 4, assuming that the other magnetic fractions contain no ZrO_2.

fifth as much as is present in the Florida deposits, and most of the samples have less than one-tenth as much TiO_2. Concentrations in this range are of questionable commercial importance at present.

Although the titanium contents of the whole samples are quite low, the titanium content of the finer size grades of all the Wabash Valley samples is greater. This suggests the possibility of screening the material, a relatively inexpensive process, and extracting titanium minerals from only the finer sized sand. This procedure seems most applicable to gravel deposits, for at least some of the oversized material would be salable as commercial gravel, thus partially avoiding the disposal of large amounts of waste material. The coarsest grained sample, number 5, contains 10.5 percent heavy constituents in the 35- by 270-mesh sieve grade, which forms 9.6 percent of the total sample. The content of titanium minerals is 1.5 percent of the 35- by 270-mesh sand, and the TiO_2 content is 0.9 percent. One ton of the original sample would contain 2.88 pounds of titanium minerals. The percentage of TiO_2 is nearly equal to that of the Florida deposits.

Although the TiO_2 content of the finer grained material in the Wabash Valley gravel-rich samples is similar to that of the Florida deposits, problems are encountered in extracting the titanium minerals from the Wabash Valley deposits that are not found in the Florida deposits. The presence of magnetite in the Wabash Valley sands would probably necessitate a preliminary separation of the magnetite. Magnetite is not reported in the Florida sands. The electromagnetic separation of ilmenite from hematite would probably be difficult, although a partial separation may be possible (Thorsen, 1964). Also, some of the ilmenite is less magnetic than some of the garnet, hornblende, and heavy rock fragments. Although ilmenite could possibly be separated from the associated magnetite, hematite, garnet, hornblende, and heavy rock fragments by a combination of electromagnetic and electrostatic processes, it is uncertain whether they or other commercial processes would be capable of separating the ilmenite economically. None of these other constituents is present in large amounts in the Florida sands.

In addition to being free of mineral separation problems, the Florida sands contain zircon and staurolite, which are sold as by-products. The Wabash Valley samples, however, contain very small amounts of zircon, and staurolite is present only in trace amounts.

The heavy fraction of the Wabash Valley sands may be suitable for multilayer filters in water filtration works, a use described for garnet by Ives (1964). A magnetite fraction also might be marketable. The possibility of marketable by-products appears less encouraging, however, in the Wabash Valley sands than in the Florida sands.

CONCLUSIONS

The heavy fractions of sands along the Wabash River are made up primarily of the silicate minerals hornblende and garnet, heavy rock fragments, and the iron-titanium and iron oxide minerals magnetite, ilmenite, and hematite. Most of the heavy minerals are in the 35- to 270-mesh size range.

Most of the samples have between 1 and 3 percent heavy minerals. Ilmenite ranges from about 0.02 to 0.3 percent, and the TiO_2 content, present as separate grains of titanium-bearing minerals, is estimated to range from 0.01 to 0.17 percent. Such percentages are much less than those of Florida sands that are being mined for their titanium minerals.

The finer size grades of some Wabash Valley samples tested have TiO_2 contents closely approaching those of the Florida sands. However, the mineral separation problems in the Wabash Valley sands appear much more difficult than the problems in the Florida sands. The possibility of marketable by-products in the Wabash Valley sands is uncertain, and the likelihood of by-products as valuable as those of the Florida sands appears doubtful.

The possibility of commercial utilization of the heavy minerals in sands along the Wabash River is questionable at the present time.

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